TIME RESOLVED MEASUREMENTS OF THE PRESSURE FIELD GENERATED BY VORTEX-CORNER INTERACTIONS IN A CAVITY SHEAR LAYER

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ABSTRACT
A 2D open cavity shear layer flow, especially its interaction with the trailing corner of the cavity, is investigated experimentally in a water tunnel, at a Reynolds number of $4.0 \times 10^4$, based on cavity length. Time-resolved PIV, at an image sampling rate of 4500 fps is used to simultaneously measure the instantaneous velocity, material acceleration and pressure distribution. The pressure is obtained by spatially integrating the material acceleration (Liu and Katz [19]). A large database of instantaneous realizations enables detailed visualization of the dynamic changes to the shear layer vortices, including convection, deformation and breakup as they impinge on the cavity trailing corner, as well as their interactions with the freshly generated boundary layer around the corner walls. The vorticity on top of the corner is originated from advected shear layer vortices and locally generated vorticity associated with the local pressure gradients. The resulting periodic recirculating flow above the corner generates the lowest mean pressure in the entire flow field. Two mechanisms with distinct characteristic frequencies affect the periodic variations in vorticity and pressure around the corner. The first is caused by streamwise transport of the large shear layer vortices. For example, when these vortices are located just upstream of the corner, they induce a downwash, which periodically eliminates the recirculating flow there. This recirculation and the associated low pressure reappear after the vortex climbs over the corner. The second mechanism involves low frequency undulations of the entire shear layer, which affect its interaction with the corner, and causes substantial variations in the pressure maximum along the vertical wall of the corner, and pressure minimum above it. These undulations are self sustained since the corner pressure fluctuations alter the recirculation speed in the cavity, which in turn change the shear layer elevation during initial rollup, and even modify the boundary layer upstream of the cavity. The time resolved pressure distribution can also be used for estimating the dipole noise radiated from the corner. The characteristic frequencies of the hydraulic and acoustic fields can be traced back to specific flow phenomena. Analysis shows that the unsteady surface pressure along the vertical wall of the trailing corner is a major dominant source of low frequency noise.

INTRODUCTION
The flow past a cavity, which involves a simple geometry, yet is rich in flow physics, has been investigated extensively over the past several decades [1-4]. Related phenomena, such as noise generation and flow-induced structural vibrations, are of practical importance in a variety of engineering applications, e.g., aircraft wheel wells, cavities in ship hulls, adjacent tall buildings, steam regulation and control valves, hydraulic gates, as well as sunroofs and opened windows in automobiles [5-6]. Interactions of the shear layer with the cavity trailing corner is of particular interest since they are presumably central to the dynamic loading on the surface and the associated noise generation [7]. Representative studies on this topic include, e.g., Tang and Rockwell [7], Lin and Rockwell[8], Rockwell and Knisely [9], Rockwell [5,10], Najm and Ghoniem [11], Pereira and Sousa[12], Chang et al [13], Haigermoser et al [14] and Lee et al [15]. They all reveal that interactions of the shear layer vortices with the flow around the corner play a major role in the local unsteadiness, turbulence and noise.

The instantaneous pressure distribution and its impact on noise is a key quantity associated with vortical motions in shear flows and their interactions among themselves and with solid boundaries. A few years ago, we developed a novel optics-based pressure technique, which is capable of measuring the instantaneous spatial pressure distribution in a non-intrusive fashion (Liu and Katz [18]). This technique originally utilized four-exposure particle image velocimetry (PIV) to measure the
distribution of the in-plane components of the material acceleration, and then integrating them by means of virtual boundary omni-directional integration algorithm to obtain the pressure distribution. The robustness of this integration method has been confirmed recently through an independent investigation carried out by Charonko et al [21]. Using this technique, we measured the velocity and pressure distributions in a high Reynolds number open cavity shear flow and compared the results to the physical appearance of cavitation as well as the measured cavitation inception indices (Liu and Katz [19]). The cavitation tests and pressure measurements revealed that the lowest pressure, and consequently, the location of cavitation inception, developed periodically above the forward corner of the cavity. Results of LES of the same geometry are presented in Shams and Apte [20]. With the appearance of time-resolved PIV measurements, as a result of the technology advancement, the same approach has been adapted for measuring the temporal derivatives of surface pressure distribution, which is essential for acoustic pressure calculations (Lasson [22]). Recent examples include Haigermoser [23] and Koschatzky et al [24] as well as Moore et al [25], where the pressure is obtained by integrating the Poisson equation.

In this paper, we use recently obtained high-speed, time-resolved PIV data to study the interaction of the shear layer vortices with the cavity trailing-corner. Our aim is to identify and quantify the primary mechanisms involved with the unsteady flow, pressure fluctuations and noise around the corner. The analysis identifies unsteady phenomena at different time scales, some that are caused by the advection of shear layer eddies, and others that occur as a result of undulations of the entire shear layer.

NOMENCLATURE

- \( a_c \) the sound speed in the fluid media
- \( C_p(x,y,t) \) pressure coefficient, \( C_p = (p - p_r)/\rho U_e^2 \)
- \( \overline{C_p(x,y)} \) mean pressure coefficient
- \( \overline{D\dot{u}} \) instantaneous material (Lagrangian) acceleration
- \( C_p(x,y) \) fluctuating pressure coefficient
- \( H \) depth of cavity
- \( L \) length of cavity
- \( L_p \) length of the horizontal line for calculation of vorticity flux
- \( N \) total number of data points in the dataset
- \( p(x,y,t) \) pressure
- \( P \) turbulent kinetic energy production rate
- \( Re \) Reynolds number
- \( t \) time
- \( \dot{U} \) instantaneous velocity vector
- \( U \) mean horizontal velocity
- \( \nabla \) mean vertical velocity
- \( U_e \) reference mean velocity upstream of cavity
- \( u,v,p \) instantaneous horizontal and vertical velocity component and pressure
- \( u',v',p' \) fluctuating quantities
- \( Y_c \) y-location of center of vorticity in the control volume for denoting the shear layer lateral position
- \( \nu \) kinematic viscosity
- \( \rho \) density of the fluid
- \( \tau_i \) viscous stress
- \( \lambda_i \) swirling strength
- \( \lambda_s \) Taylor transverse microscale
- \( \omega_i \) spanwise vorticity
- \( \delta \) time interval between sample images

EXPERIMENTAL SETUP AND PROCEDURES

The experiment has been conducted in a small water tunnel described in Gopalan and Katz [26] and Liu and Katz [18]. The 2-D open cavity test model is sketched in Fig. 1. The 38.1 mm long, 50.8mm wide and 30.0 mm deep 2-D cavity is constructed in a transparent acrylic insert that is installed in the 50.8×63.5 mm test section. The test model has a contraction ramp leading to the cavity, and a diffusing ramp downstream of the cavity. A 13 mm long region with tripping grooves, each with a notch depth of 0.46 mm and width of 1.00mm is machined at the beginning of the contraction ramp in order to trip the boundary layer. Thus, the separating boundary layer at the beginning of the cavity is turbulent. The mean velocity
above the cavity is 1.20 m/s, corresponding to Reynolds numbers of 4.0\times10^4 based on cavity length.

To perform the time-resolved, 2D PIV measurements, we utilize a Photonics DM60-527 Nd:YLF laser that has a maximum pulse rare of 10 kHz, and pulse width of 100 ns. The images are recorded at 4500 frames per second by a PCO.dimax CMOS camera, at a resolution of 1008\times1000 pixels, giving a Nyquist frequency of 2250 Hz for the velocity. To synchronize the laser with the camera, we use Quantum Composer model 9618 pulse generator. The selected temporal resolution is sufficient for resolving the Kolmogorov time scale, found to be 673 \mu s, based on curve fits to the spatial energy spectra to estimate the dissipation rate. The size of the field of view is 25\times25 mm. With an appropriate setting of the concentration of seed particles, 8-12\mu m diameter hollow glass spheres with specific gravity of 1.05-1.15, we are able to use an interrogation window size of 16\times16 pixels, corresponding to 0.4\times0.4 mm. This size is similar to the estimated Taylor transverse microscale, \lambda_T, of 0.5 mm, but is an order of magnitude larger than the Kolmogorov length scale of 26 \mu m. A 50\% overlap between the interrogation windows gives a vector spacing of 0.2 mm. We use an in-house developed software (Roth [27] and Roth and Katz [28]) for calculating the velocity. The entire dataset for each field of view consists of 10,000 sequentially obtained instantaneous realizations over a period of 2.22 sec.

The procedures for obtaining the velocity and the material acceleration, though still following the principle described in [18], have been modified to take advantage of the continuous data series. Analysis of each pair of consecutive images provides an instantaneous velocity distribution, and the entire set provides a time series \vec{U}_i, \vec{U}_i, \vec{U}_i, ... \vec{U}_i. Five consecutive images are used for calculating the acceleration. Selecting, e.g., five consecutive images recorded, to calculate the velocity field at time \( t_i \), we use

\[
\vec{U}_i = \frac{\left( \vec{D}_{i,i+1} - \vec{D}_{i,i-1} \right)}{(2 \delta)} \tag{1}
\]

where \( \vec{D}_{i,i+1} \) is the result of cross correlating image \( i \) with image \( i+1 \). To calculate the in-plane projection of material acceleration, we have

\[
\frac{D\vec{U}_i}{Dt}(\vec{x},t_i) \approx \frac{\vec{U}_{i+1}(\vec{x}_i + \vec{D}_{i,i+1},t_{i+1}) - \vec{U}_{i+1}(\vec{x}_i + \vec{D}_{i,i+1},t_i)}{2 \delta} \tag{2}
\]

A similar approach is used in de Kat and van Oudheusden [29]. We have also adapted an improved virtual boundary, omnidirectional integration method, featuring circular virtual boundary instead of the rectangular one described in [18]. A discussion on validation of the modified pressure
reconstruction code was presented at Liu and Katz [30] and will appear in future publications by the authors as well.

RESULTS

Time-Averaged Velocity and Pressure Distributions

As illustrated in Fig. 1, the origin of the coordinate system is placed at the leading edge of the cavity, with the x and y axes pointing downstream and upward, respectively. Since the 25×25 mm field of view does not cover the entire cavity, we have recorded data in several sections, but in this paper focus on the flow around the cavity trailing corner. Fig. 2 shows the time-averaged velocity and pressure distributions overlapped with the absolute streamlines. The normalized mean streamwise velocity (Fig. 2(a)) drops from 1 to 0.3 across the shear layer, which has a width of roughly 5 mm \((0.13L)\), implying that the characteristic mean shear is 168 s\(^{-1}\) \((5.3U_e/L)\). As the shear layer approaches the trailing wall, it is subjected to an adverse pressure gradient in the vicinity of the trailing corner and therefore decelerates, forming a mean stagnation point 1 mm \((0.026L)\) below the trailing corner (Fig. 2(c)). The mean flow then accelerates around the corner, and creates a pressure minimum on top of it, at about 0.5 mm \((0.013L)\) downstream from the tip. As discussed in details in [31] for a higher velocity, this pressure minimum is the first site of cavitation inception. Although the mean velocity remains positive above the corner, at least at the scale of the interrogation windows, examination of the particle traces shows that reverse flow occurs intermittently very near the wall, at scales that are a small fraction of the window. As reported in Lin and Rockwell [8], we also observe the downward "jetlike" flow (Fig. 2(b)) close to the cavity vertical wall, which entrains part of shear layer into the cavity. The magnitude of the velocity in the jetlike region is quite high, reaching about 40% of the freestream velocity, in contrast with the typically low velocity of 10-15% of \(U_e\) within the recirculation region.

Reynolds Stress and RMS Pressure Distributions

The distributions of the Reynolds stresses and the rms values of pressure fluctuations are shown in Fig. 3. The largest
streamwise velocity fluctuations (Fig. 3(a)), with values that are almost twice as high as those in the shear layer, occur on top of the trailing corner. Conversely, the vertical velocity fluctuations (Fig. 3(b)) peak in the shear layer with values that are 40-50% smaller than those of the streamwise component. After impingement on the corner, the shear layer separates with one part climbing around the corner, and the other entrained into the cavity along the vertical wall. The turbulence in both layers subsequently decays. The highest values of the Reynolds shear stress are also measured in the shear layer, peaking just upstream of the impingent point, and then decay slowly with opposite signs in the layers propagating above and along the trailing walls. These trends are consistent with those presented Lin and Rockwell [8]. One noteworthy phenomenon is the change in Reynolds shear stress sign just above the tip of the corner. It is likely that this phenomenon is a result of high negative production rate of the Reynolds shear stress there due to the large negative values of $\frac{\partial^2 \bar{u}^2}{\partial x^2}$ that occur as the wall-normal velocity decays rapidly around the corner. It should also be noted that the turbulent kinetic energy production rate is also negative very near the corner, in part due to the rapid streamwise acceleration of the flow there, and in part due to the negative shear stress.

The highest pressure-fluctuations occur around the corner, as shown in Fig. 3(d). This trend is a result of several co-occurring phenomena, including periodic impingement and breakup of the shear layer vortices, along with low frequency vertical undulations of the entire shear layer. Both contributors are discussed later in this paper. Since we place the reference pressure at the upper-left corner in the field of view, the pressure fluctuations there, by definition, zero in that point. The pressure fluctuations increase gradually with increasing distance from this point. Since the pressure fluctuation auto-correlation function (not shown) decays at about 15 mm, the choice of the reference point should not have a significant effect on the rms statistics beyond this distance from this point.

**Interaction of the Shear Layer Vortices with the Corner.**

A sequence of sample snapshots demonstrating the time-evolution of the instantaneous swirling strength and pressure distributions are shown in Fig. 4. The swirling strength, $\lambda_{ci}$, [32-34] is the imaginary part of the complex eigenvalue of the local velocity gradient tensor, which represents the strength of local swirling motion and can be used to identify vortices in the flow field. The pseudo-streamlines are obtained subtracting half of the external velocity from each vector. As the large shear layer eddies impinge on the trailing corner, they are deformed, sheared, and break, periodically feeding vorticity to the boundary layers on the horizontal and vertical corner walls (Fig. 4 (d1)). At the instants corresponding to Fig. 4 (a1) and (b1), a local region of high vorticity forms right above the corner, and is attached for part of the cycle. During this phase, a high pressure peak appears in front of the corner, and a negative one above it, indicating that the flow near the corner is subjected to high pressure gradients (Fig. 4 (a2) and (b2)). The origin of this high vorticity above the corner is discussed in the next subsection.

The high corner pressure peaks disappear periodically when the shear layer eddy is located just upstream of the corner or starts climbing around it (Fig. 4 (c) and (d)). These peaks reappear when the eddies are located further upstream or are located entirely above the corner (Fig. 4 (a) and (b)).
Magnitudes of these peaks are also affected by the low frequency undulations of the entire shear layer, as discussed later. Disappearance of the pressure peaks, especially the negative one, which also eliminates the cavitation above the corner, occurs as a result of vortex-induced downwash [19]. The positive peak disappears when the vortex occupies the space upstream of the corner. Conditional sampling of the flow field based on the direction of the mean wall-normal velocity component in a small sample area located above the corner (Fig. 5) confirms the relationship between vortex location, downwash and magnitude of pressure peaks.

**FIGURE 5.** CONDITIONALLY AVERAGED PRESSURE DISTRIBUTIONS WHEN (a) V>0 AND (b) V<0 IN THE AREA INDICATED BY THE BLACK RECTANGLE.

**FIGURE 6.** VISCOS PRODUCTION OF VORTICITY ON CAVITY TRAILING CORNER DUE TO PRESSURE GRADIENT. (a), POSITIONS OF CONTROL PLANE FOR VORTICITY FLUX; (b), VORTICITY FLUX THROUGH THE CONTROL PLANE; (c), COMPARISON OF VORTICITY FLUX THROUGH THE BOTTOM PLANE WITH PRESSURE GRADIENT.
Local Vorticity Generation due to Pressure Gradients

To investigate the origin of the vorticity, which seems to be locked to the top of the corner during part of the cycle, we compare the vorticity flux, \( \int \omega \cdot n \, dl \), across three lines (orange, purple and black) illustrated in Fig. 6a. The first is a vertical orange line that coincides with the corner tip and represents the vorticity arriving from the shear layer. The second is a 0.8 mm long horizontal purple line that starts at the corner, and located 0.15mm away from the surface, which is used for estimating the local vorticity production along the wall. The third is a short (again 0.8 mm long) vertical black line, selected to include the vorticity flux that would most likely be entrained into the corner area. Sample time series showing the fluxes along with the corresponding time series of pressure are presented in Fig. 6(b). Note that since \( \omega_z \) is for the most part negative, a negative flux would increase the vorticity above the corner. As is evident, the entire flux coming from the shear layer has peaks that are 3-4 times higher than those that are generated locally. However, the vorticity flux that would be entrained into the corner, i.e. the flows through the short vertical line, is of the same magnitude as that generated at the wall. The local production seems to be periodic and peaks during periods of low pressure above the corner. In several cases, the local maximum occurs when the total flux from upstream is low. The flow patterns corresponding to the wall flux maximum at \( rU_c/L = 1.204 \) and 1.393 are shown in Fig. 4 (a2) and (b2), i.e. when a vortex and a pressure minimum are locked to the tip of the corner. At the same time, remnants of one shear layer eddy are already located above the corner, and a second one is still situated in the shear layer “far” upstream of the corner. To explain the mechanism involved with local vorticity production, one can express the momentum equation on the solid boundary as

\[
\frac{1}{\rho} \frac{\partial p}{\partial x}_{\text{wall}} \approx -\frac{1}{\rho} \frac{\partial \omega}{\partial y}_{\text{wall}}
\]

(3)

as pointed out by Lighthill [35], and investigated in detail by Andreopoulos and Agui [36]. A comparison between the time series of pressure gradient, spatially averaged along the horizontal line, and the vorticity flux across it is presented in Fig. 6(c). Clearly, the shape of these time series are quite similar, they peak at the same time (ignoring spikes), and have a similar characteristic frequency of about 50Hz, matching the shedding frequency of the large shear layer eddies. The correlation coefficient between the pressure gradient at the corner and the vorticity flux from the bottom, averaged over the entire database is 0.50, quite a significant value. Thus, one can conclude that the local production of vorticity is a result of viscous diffusion from the wall induced by the high pressure-gradients near the corner during part of the cycle. The comparison of fluxes very near the corner indicates that viscous production accounts for a substantial fraction of the vorticity occupying the corner during low-pressure periods. Accordingly, the local vorticity production is also significantly correlated with the local pressure, with a correlation coefficient of 0.51. For comparison, the correlation coefficient between pressure and vorticity flux across the short vertical line is 0.14, i.e. much weaker, confirming the substantial role of local vorticity generation.

Acoustic Field Generated by Shear Layer Interactions with the Corner

Following Haigermoser [23], Koschatzky et al [24] and Moore et al [25], the time-resolved pressure distribution along the wall, can be used to obtain the acoustic pressure field generated by the shear layer-cavity corner interactions. Consequently, one can identify specifically which flow phenomenon affects the acoustic pressure and to what extent. For completeness, we provide a brief summary about the method used for obtaining the acoustic field. The theory is
based on Lighthill's acoustic analogies [37], which decouples the acoustics problem from that of the fluid flow [22][24]. The wave equation for sound propagation derived by Lighthill is as follows:

\[
\frac{\partial^2 \rho}{\partial t^2} - a_s^2 \frac{\partial^2 \rho}{\partial x^2} = \frac{\partial^2 T_0}{\partial x \partial t}
\]  

(4)

where \( \rho \) is density, \( T_0 = \rho u_j - \tau_y + \left( p - a_s^2 \rho \right) \delta_y \), \( a_s \) is the sound speed and \( \tau_y \) is the viscous stress. Curle [38] incorporated non-moving solid boundaries to the model, and obtained the following expression for the acoustic pressure:

\[
p(x,t) - p_a = \frac{1}{4\pi r} \int T_0 \frac{\partial^2 T_0}{\partial x^2} \frac{1}{r^3} dV(y) + \frac{1}{4\pi r} \int \left( p \delta_y - \tau_y \right) dS(y)
\]  

(5)

where \( V \) is the volume and \( S \) is the surface area. Further modifications to variables ([22] [23] [40]) gives

\[
p(x,t) - p_a = \frac{1}{4\pi r} \int \left( \frac{\partial}{\partial t} \frac{\delta_y}{a_s} + \frac{p \delta_y}{a_s r^2} \right) dS(y)
\]  

(6)

For an incompressible flow, the volume integral becomes negligible [22], resulting in the following simplified expression for the acoustic pressure field generated by interaction of the flow with the solid boundary (dipole noise) [23] [24]:

\[
p(x,t) - p_a = \frac{1}{4\pi r} \int \left( \frac{\partial}{\partial t} \frac{\delta_y}{a_s} + \frac{p \delta_y}{a_s r^2} \right) dS(y)
\]  

(7)
where \( r \) is the distance from the "observer" to the sound source. Thus, the acoustic pressure depends on two terms: (i) The first involves the temporal derivative of the surface pressure and decays as \( r^{-2} \). (ii) The second term contains the pressure, and decays as \( r^{-1} \), i.e. faster than the former.

In this paper, we use Eq. (7) to evaluate the acoustic radiation from the cavity trailing corner that falls within our field of view. The distribution of the sound pressure level,

\[
SPL = 20 \log_{10}(p_{rms}/p_{ref}),
\]

where \( p_{ref} = 20 \mu \text{Pascal} \), is shown in Fig. 7(a). Noise spectra obtained in a similar fashion have been presented [24] and [25]. Note that the length scales of this plot are much larger than those presented in the rest of this paper. As expected, the sound level decays with distance from the source. To investigate the characteristic frequencies imbedded in the acoustic field, we select four points at different locations, and perform spectral analysis. The resulting power spectral densities are plotted in Fig. 7(b). The spectral peaks can be categorized into the following three groups: (i) Low frequency: e.g. the peak at 4.4 Hz and others below 20Hz, which, as shown later, are associated with vertical undulations of the entire shear layer and recirculation in cavity. (ii) Peaks at 26, 33, 40, 48 Hz, which are associated with the large eddies in the shear layer, in agreement with theoretical predictions of the cavity shear layer modes. Based on Martin et al [41], Blake [42] and Rossiter [43], these modes can be calculated from

\[
fL/U_c = n \pm 0.25, \quad n = 2, 3, ... \quad (8)
\]

where \( U_c \) is the convection speed of eddies in the shear layer, estimated as 50% of the freestream velocity. We do not include the \( n=1 \) modes since they merge with those of shear layer undulations. (iii) High frequency noise at frequencies exceeding 97.4 Hz, which extends to the entire range of resolvable time scales. This range is associated with the broad range of turbulence scales, including the shear layer secondary structures. This part of the spectrum is also affected by noise introduced by time derivation of the pressure, which is difficult to assess quantitatively.

**Sample Spectral Analysis of Flow Quantities**

To identify the origin of the characteristic acoustic spectral peaks (Fig. 7(b)), we also perform spectral analysis for a variety of flow quantities, at different locations. Fig. 8 (a) indicates two sample locations: Point A is located in the shear layer “far” upstream of the corner, and point B is located within the region of previously discussed pressure minimum on top of the trailing corner. Spectra of pressure and its temporal derivative at point B are shown in Fig. 8 (b) and (c), respectively, while spectra of streamwise velocity and pressure at point A are shown in Fig. 8 (d) and (e), respectively. Furthermore, to identify flow events responsible for the acoustic characteristics, Fig. 8(f) shows the spectrum of the circulation within the control volume indicated by the orange rectangular box in Fig. 8(a). The size of the control area used for calculating the circulation is selected to cover an entire large-scale eddy. The circulation is calculated by spatially integrating the vorticity. As shown in Fig. 8 (b), pressure peaks ranging from 4.4 to 99 Hz are found in the pressure spectrum of point B. In Fig. 8 (c), although the low frequency peaks are not prominent, which is inherent to be associated with a time derivative, peaks in the frequency range of 40 - 300 Hz are evident. As expected, within the frequency resolution of the spectral analysis, 2.2 Hz, the frequency peaks seen in Fig. 8(b) and (c) agree with those found in the far field acoustic spectra (Fig. 7(b)).

As demonstrated in Fig. 8(f), the circulation spectrum has two distinct frequency peaks, at 46 and 99 Hz, that can also be found in all the flow-related spectra of both points, as well as in the acoustic spectrum (Fig. 7(b)). Examination of the time series of velocity, pressure and circulation in the control area confirms that these spectral peaks are caused by convection of the shear layer eddies. Existence of two peaks is associated with phases in a pairing process of two eddies that frequently occurs in the vicinity of the orange control volume. Sometimes, these eddies appear organized in a horizontal line, i.e. pairing has not occurred yet, and the prominent frequency is 99 Hz. More often than not, the eddies appear rolling round each other, and combined, they produce the 46 Hz peak.
To explain the origin of the low frequency peaks, i.e. at 4.4-20 Hz found in spectra shown in Fig. 8(b), (d), (e) and (f) as well as in Fig. 7(b), Fig. 9(c) shows the entire time series of low-pass filtered (cut-off frequency 500 Hz) velocity $u$ at point A. As is evident, the velocity at this fixed location fluctuates at low frequency. The amplitude of this fluctuation is substantial, causing the velocity magnitude to vary between 40 to 100% of $U_e$. These fluctuations are not associated with the transport of the shear layer eddies that occurs at a much higher frequency, and cause the spiky appearance of the long time series in Fig. 9(c). Two typical flow and pressure distributions occurring when the instantaneous velocity is low and high are presented in Fig. 9(a) and (b), respectively. They show that the location of the entire shear layer fluctuates vertically, i.e. it undergoes vertical flapping. When the shear layer is high (Fig. 9(a)), the velocity at point A is low, and when the shear layer is high, the same point is located at the top of the shear layer, and the velocity there is almost equal to the freestream value. This phenomenon has been referred to before as "jitter" (Rockwell and Knisely [9], Najm and Ghoniem [11] and Pereira and Sousa [12]), and attributed to instabilities of the large recirculation motion within the cavity (Najm and Ghoniem [11]).

To characterize the vertical undulation of the shear layer, we examine the low-pass filtered (cut-off frequency 20Hz) vertical location of the vorticity center ($Y_c$) within the area enclosed by the orange control volume shown in Fig. 8(a). The low frequency time variations of $Y_c$, shown in Fig. 10(a), represent the vertical position of the shear layer. The spectrum of the unfiltered location of the vorticity center, which is presented in Fig. 10(b), has a clear peak at 4.4Hz. The magnitude of the correlation between the low-pass filtered vorticity center with the low-pass filtered "far field" acoustic pressure at the point labeled as A in Fig. 7(a) is -0.47. To further identify the primary source of low frequency noise, we also decompose the acoustic signal to terms involving the pressure and its time derivatives, as well as to contributions to sound radiated from the vertical and horizontal walls of the cavity corner. Each of the terms is correlated separately with the time series of $Y_c$. We find that the correlations of $Y_c$ with terms involving the pressure temporal derivative are insignificant (less than 0.1 in magnitude). Conversely, the correlations of $Y_c$ with the pressure terms integrated over the front and top walls of the cavity corner are -0.72 and 0.14, respectively. Thus, the low frequency part of the noise spectrum primarily involves the pressure terms, as expected since spectra of time derivatives are inherently biased towards high frequency. Furthermore, the vertical wall is a primary contributor to the low frequency noise. The close relationship between the pressure along the vertical wall and undulations of the shear layer has also been confirmed by correlating $Y_c$ with the pressure at several locations along the walls. The most significant correlation of -0.81 is obtained close to the impingement point.

The vertical undulations of the shear layer have a significant impact on virtually all flow quantities in the cavity flow field. To demonstrate this effect, we examine several variables, conditionally sampled based on the values of $Y_c$. Fig. 10 and 11 compare some characteristic results when $Y_c$ falls within the upper 30% of its full range to those occurring when $Y_c$ falls within the lowest 30%. These bounds are indicated in Fig. 10(a). Profiles of the conditionally averaged streamwise velocity and Reynolds shear stress at the upstream entrance to the present field of view are shown in Fig. 10 (c) and (d), respectively. The 1.38 mm (i.e., 0.036L) vertical separation between profiles is evident in both cases. However, by shifting the high $Y_c$ data down, as demonstrated in Fig. 10(e) and (f), one can see that the differences between velocity profiles are small, and that the shear stress distribution indicates that the turbulent shear layer is slightly wider when the $Y_c$ is low, suggesting that the turbulence is more sensitive to undulation than the mean flow quantities. Thus, for the most
part, the vertical undulations do not change the shape of the shear layer significantly.

However, the shear layer undulations change its interaction with the corner significantly, as demonstrated in Fig. 11 by distributions of conditionally averaged pressure, vorticity and rms values of horizontal velocity. The differences in the vertical positions of the shear layer are evident in all of the distributions. In particular, the high magnitude of the mean pressure peaks upstream and above to corner when $Y_c$ is low, decreases by 48% and 40% respectively on the front and upper surfaces of corner when $Y_c$ is high. The overall vorticity flux above the corner is high when $Y_c$ is high, and the vorticity flux along the vertical wall is high when $Y_c$ is low. This trend indicates, as expected, that larger fractions of the shear layer are entrained back into the cavity when the shear layer is low. This latter trend is consistent with conclusions based on flow visualizations performed by Tang and Rockwell [7]. Accordingly, the velocity fluctuations above the corner are higher when a larger fraction of the shear layer escape from the cavity, i.e. when $Y_c$ is high, in comparison to those measured at low $Y_c$. As for the pressure, its peaks in front of the vertical wall increases when higher momentum fluid impinges on it, i.e.
when the shear layer is low. At the same phase, the high negative pressure peak on top of the corner is directly associated with an increase in the local flow curvature as the faster flow impinges on the wall, and then accelerates around the corner. Further discussions on the mechanism that causes the low-frequency undulation can be found at Liu and Katz[44].

SUMMARY AND CONCLUSIONS
Dynamic interactions between a cavity shear layer and its trailing corner are investigated based on recently obtained, PIV based, time series of velocity and pressure distributions. Two primary mechanisms with distinctly different characteristic frequencies affect the periodic vorticity flux and generation as well as pressure variations around the corner. The first mechanism involves interactions of the large-scale, organized shear layer vortices with the corner. The velocity and pressure induced by these vortices cause periodic formation of pressure maxima in front of the cavity corner, and pressure minima above it. The vorticity flux near the wall, and consequently the magnitude of the pressure minimum there, is equally affected by local viscous generation due to the high-pressure gradients there, and by transport of the shear layer eddies. This pressure minimum is lower than any negative pressure peak in shear layer, and consequently, it is the primary site for cavitation inception in the cavity shear flow.

The second unsteady flow mechanism is characterized by low frequency undulation in the elevation of the shear layer. The flow impinging on the vertical wall of the cavity with slowly varying bulk momentum due to low frequency undulation. Consequently, the stagnation pressure there along with the pressure minimum on top of the cavity are subjected to low frequency fluctuation. The elevation also affects what fraction of the shear layer is entrained back into the cavity, and what fraction escapes from it. As a result, the up and down elevation also impacts the distribution of turbulence around the corner. We have not discussed this issue in this paper, but this periodic change in the momentum of the fluid entrained into the cavity represents part of a feedback mechanism that controls the elevation of the shear layer. Entrainment of high momentum fluid when the shear layer is low increases the overall pressure in the cavity, and consequently lifts the entire shear layer, starting even in the boundary layer upstream of the inlet corner to the shear layer (not shown). Once the shear layer is lifted, the pressure in the exit corner and momentum flux along the forward vertical wall decrease, causing a reduction in pressure within the cavity, and a subsequent downward shift in the elevation of the shear layer. Existence of feedback mechanisms in cavity shear layers have been suspected before [1-12].

Using the time resolved pressure distribution along the surface of the corner, we calculate the dipole sound generated and radiated from both sides of the cavity trailing corner. Spectral and correlation analyses are used for identifying the primary mechanisms involved with sound generation. We find that the sound pressure is impacted by the flow frequency undulations at 4.4 - 20 Hz, as well as by the flow phenomena involved with vortex-corner interactions in the 20 – 100 Hz range. The pressure along the forward face of the cavity has a high impact on the radiated sound at short distances.

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REFERENCES


